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DEVELOPMENT OF A SIMPLE RUNWAY WAVINESS MEASURING SYSTEM

by

F. J. PLANTEMA and J. BUHRMAN

OCTOBER 1963

NORTH ATLANTIC TREATY ORGANIZATION
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ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

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PREFACE

The following report to the Structures and Materials Panel of AGARD is intended primarily to give a survey of the work carried out by the National Aero- and Astronautical Research Institute (NLR), Amsterdam concerning the development of a runway roughness measuring system. This work was carried out under three contracts, granted to the NLR upon recommendation of the Panel, viz.:

(1) SHAPE Order 180/59 (AGARD Authority 81-59), dated 19 October 1959, 'Study of runway roughness measuring systems'.

(2) SHAPE Order 155-61 (AGARD Authority 64-61), dated 18 February 1961, 'Preparation of a specification and the principal design drawings of a runway roughness measuring system'.

(3) SHAPE Order 155-62 (AGARD Request 47/62), dated 15 February 1962, 'Further study of runway roughness cart', and Modification No.1 (AGARD Request No. 149/62), dated 19 December 1962.

The report consists of two parts. Part I, which was completed in March 1963, gives a general survey of the work carried out under the three contracts and a description of the principal results obtained. In order to give the reader a better understanding of the problem under consideration, it opens with a brief review of the collection and presentation of statistical data on runway roughness, which was carried out as a collaborative undertaking in a number of NATO countries. A few aspects of runway roughness criteria are also mentioned.

More details on the work carried out under the contracts (1) and (2) mentioned above are given in a few previous interim reports, entitled:

'Roughness measuring systems for runways and taxi-tracks', by F.J. Plantema and J. Buhrman. NLL Note MS-60-45, 15th July 1960. Also contained as Appendix C in the 'Report of the working party on runway roughness, June 6-7, 1960 et seq.', AGARD Structures and Materials Panel.

Supplement to: 'Roughness measuring systems for runways and taxitracks', by F.J. Plantema and J. Buhrman. NLL Note MS-61-3, 30th January 1961.

Progress report on the development of a runway roughness measuring cart', by J. Buhrman and F.J. Plantema. NLL Note MS-61-19, 15th April 1961.

Part II of the report contains a more detailed treatment of the work carried out under the final contract (3). It was originally prepared as a separate report and completed in June 1963. When it had been decided to publish the two parts as one report, slight modifications only were made in order to avoid a considerable delay. Therefore, a certain amount of duplication of information occurs.

The contract (3) has been terminated by the provision to the Structures and Materials Panel of AGARD of detail drawings of the proposed measuring system, together with a report containing the manual of the system, a list of requirements for the camera and data on a commercially available camera.

SUMMARY

A review is given of the work concerned with surface waviness of runways and taxi-tracks carried out under the auspices of the Structures and Materials Panel of AGARD. The collection of statistical data and the advantages and disadvantages of various forms of presentation of these data are discussed. Runway roughness criteria are dealt with very briefly.

A discussion is given of the shortcomings of existing systems and methods for measuring the range of wavelengths from 4 feet to 200 feet. An optical system developed by the NLR which avoids these shortcomings is described.

The results of a series of test runs with the NLR-system are compared with the results of conventional level-and-rod measurements. The agreement between the derived characteristics (power spectrum and deviations from straight lines) is very satisfactory. The agreement between the runway profile as obtained by integration of the measured slopes and the true profile is limited, since the system only gives a true reproduction of the components in the design range of wavelengths.

It is concluded that the NLR-system shows favourable characteristics as a rapid and simple measuring system. A few current and possible future extensions of the work are dealt with briefly.

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SOMMAIRE

On présente une revue des travaux intéressant la nature onduleuse de la surface des pistes d'envol et des voies de roulement au sol réalisées sous les auspices du groupe Structures et Matériaux de l'AGARD. On examine le rassemblement des données statistiques, ainsi que les avantages et les inconvénients que présentent diverses formes d'exposition de ces données. On traite très brièvement des critères de rugosité des pistes d'envol.

On relate une discussion sur les défauts des systèmes existant actuellement et les méthodes de mesure de gamme de longueurs d'onde de 4 à 200 pieds (1,22 à 61 mètres). On décrit un système optique mis au point par le NLR et qui permet d'éviter ces imperfections.

Les résultats d'une série de parcours d'essai avec le système NLR sont comparés aux résultats des mesures classiques avec niveau et mètre. La concordance entre les caractéristiques dérivées (spectre de puissance et déviations de lignes droites) est très satisfaisante. La concordance entre le profil de la piste d'envol tel qu'obtenu par intégration des pentes mesurées et le profil réel est limitée, car le système ne donne qu'une reproduction vraie des composantes dans la gamme d'étude des longueurs d'onde.

On conclut que le système NLR révèle des caractéristiques favorables comme système de mesure rapide et simple. On examine succinctement quelques extensions de ces travaux, tant actuelles que possibles pour l'avenir.

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NOTATION

a	wheel spacing of measuring cart (Fig. 8)
A	transfer factor of measuring system, i.e. ratio between measured and actual slope or elevation amplitudes of sine waves
d	elevation deviation from straight line of length l (Fig. 3)
l	length of straight line connecting two points of runway surface (Fig. 3)
L	wave length of sine wave
n	measuring system parameter (Fig. 8)
x	abscissa of runway surface
y	elevation of runway surface
Δy	difference between two successive values of y
σ	standard deviation (r.m.s. value) of y
φ	slope of runway surface
$\Phi(\Omega)$	power spectral density function
Ω	frequency parameter ($= 2\pi/L$)

DEVELOPMENT OF A SIMPLE RUNWAY WAVINESS MEASURING SYSTEM

F.J. Plantema* and J. Buhrman*

PART I

SURVEY OF INVESTIGATIONS ON RUNWAY WAVINESS INITIATED BY AGARD

I.1 INTRODUCTION

In this Part a brief review will be given of the work concerned with surface waviness of runways and taxi-tracks (runway roughness), that has been carried out under the auspices of the Structures and Materials Panel of the Advisory Group for Aeronautical Research and Development over a period of more than five years.

The problem was first felt in the United States where already in 1954 results of measurements of a few runways were published as NACA TN 3305. In this paper the frequency of occurrence of large load applications in routine ground airline operations was mentioned as the incentive to carry out the measurements. In an introductory paper for the Structures and Materials Panel in October 1958 Dr. Houbolt of the N.A.S.A. mentioned the following difficulties encountered as a consequence of runway roughness:

(1) Structural failures of certain large aircraft carrying heavy masses on outboard regions of wings, such as engines, tanks and missiles.

(2) Difficulties in reading panel instruments in the cockpit.

(3) Concern about the fatigue life of the aircraft structure.

(4) Pilot complaints concerning taxiing behaviour, such as porpoising and a tendency to become prematurely airborne.

Factors contributing to the increased severity of the problem have been the use of outboard masses mentioned under (1), the use of higher-pressure tires, and the increased taxiing speeds.

Since the problem was considered to be mainly of importance from the point of view of aircraft loads it was included on the programme of work of the Structures and Materials Panel. Up to now the following aspects have been studied:

Collection of statistical data for a number of runways and taxi-tracks in various NATO countries.

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*National Aero- and Astronautical Research Institute (NLR), Amsterdam

An attempt to establish criteria for runways, either newly constructed or in need of repair, based on a correlation of the statistical data with the operational experience on a number of runways.

A study of systems for measuring the waviness properties of runways and taxi-tracks relatively quickly and inexpensively, followed by the design of a new measuring system and the testing of a simplified prototype system. For the work under this item the National Aero- and Astronautical Research Institute (NLR), Amsterdam was granted a few contracts and this work has now been completed.

The Structures and Materials Panel has not yet concerned itself with the determination of the aircraft loads following from the runway roughness input; it is felt that this problem contains several aspects deserving further study.

I.2 COLLECTION OF STATISTICAL DATA OF RUNWAYS AND TAXI-TRACKS

The N.A.S.A. had kindly offered to evaluate the results of all the measurements obtained from an AGARD cooperative programme in the same way as it had evaluated previous U.S. measurements. Consequently, the measurement technique used in the United States was also adopted by the other NATO countries contributing to the collection of statistical data. Use was made of the standard level-and-rod apparatus; a vertical rod with scale division was moved along a line parallel to the axis of the runway with a measuring interval of 2 feet, and was read by means of a horizontal surveyor's level. In this way the elevation of the runway surface was determined with respect to a horizontal reference plane.

The measuring interval of 2 feet was selected as half the shortest wavelength one desired to include*. This shortest wavelength L_{min} is determined by the taxiing speed V and the highest resonant frequency f likely to be excited by the runway roughness. Taking $V = 100$ miles per hour (160 km/h) and $f = 35$ cycles/sec, it follows that $L_{min} = 4$ ft approximately. The longest wavelength considered in the NASA evaluation of the measurements was $L_{max} = 160$ ft (50 m approx.). The readings were made to an accuracy of 0.001 foot (0.3 mm), the last decimal being estimated. This accuracy seems to be exaggerated if it is observed that incidental surface irregularities are likely to be of the order of 0.01 foot. According to U.S. data the average speed of measuring amounted to 250 ft (75 m) per hour approximately.

The results of the measurements for 34 runways are summarized in Reference 1; detailed tabulated data are given in a series of AGARD Research Memoranda. Up to 1961 a total of about 60 runways and taxi-tracks in the United States and Europe were processed. In Reference 1 the results are presented graphically in the form of surface profiles and power spectra.

The surface profile is useful to indicate locations where the runway is of good or bad quality. It can also be used to determine the deviations from imaginary straight edges which are commonly used as a criterion for runway construction. For example, a standard criterion is that there shall be no gap exceeding 0.1 inch or 0.125 inch under a straight edge of 10 foot length placed anywhere on the runway surface.

* Sampling a disturbance at intervals of one-half the shortest wavelength present specifies the disturbance.

The power spectrum is generally used nowadays in the treatment of stochastic phenomena because it forms part of a modern mathematical theory of such phenomena. The theory was developed some twenty years ago and the power spectrum was first used for aeronautical applications in the United States about 10 years ago. Some insight into the significance of the power spectrum can be obtained in the following manner.

A periodic function $y(x)$ of x with period L_0 can be written in the form of a Fourier series:

$$y(x) = \sum_{n=1}^{\infty} A_n \sin\Omega_n x + \sum_{n=0}^{\infty} B_n \cos\Omega_n x , \tag{1}$$

where $\Omega_n = 2\pi n/L_0$.

The constants A_n and B_n can be determined by means of the standard procedures of Fourier analysis. The components with the frequency Ω_n can also be written as

$$A_n \sin\Omega_n x + B_n \cos\Omega_n x = C_n \sin(\Omega_n x + \varphi_n) \tag{2}$$

where $C_n = \sqrt{(A_n^2 + B_n^2)}$ and $\varphi_n = \text{arc} \tan B_n/A_n$.

The series thus consists of sines which have different phases. If $y(x)$ is supposed to be the displacement of a vibrating system (x being the time), then C_n is the amplitude of the component having the frequency Ω_n and C_n^2 is a measure of the energy contribution due to this component. The total energy of the system is equal to the sum of the energy contributions of the components (which is not true for the amplitudes). The bar graph of Figure 1, where $C_n^2 L_0/4\pi$ has been depicted as a function of Ω_n , is called the discrete energy, or 'power spectrum' of $y(x)$. In Figure 1 the area of the column between Ω_n and Ω_{n+1} is equal to $\frac{1}{2}C_n^2$ and the total hatched area is equal to the average value of $y^2(x)$ over the period L_0 . The expression 'power spectrum' is also used for other phenomena, such as runway roughness, where no real energy is involved.

If now the function $y(x)$ is non-periodic then the limiting case $L_0 \to \infty$ must be considered. The discrete spectrum then becomes a continuous power spectrum having as abscissa $\Omega = 2\pi/L$, where Ω and L are continuous variables. The ordinate is usually called the power spectral density function and denoted as $\Phi(\Omega)$. $\Phi(\Omega)d\Omega$ now is a measure of the energy contribution of the components having frequencies between Ω and $\Omega + d\Omega$, i.e. wavelengths between $2\pi/\Omega$ and $2\pi/(\Omega + d\Omega)$. If $\Phi(\Omega)$ is finite everywhere then the energy of the component having one discrete frequency Ω is equal to zero.

An example of a power spectrum, relating to the elevation of a runway surface, is given in Figure 2†. This spectrum was computed for $0.0349 \leqslant \Omega \leqslant 2.094$ and thus covers wavelengths ranging from 3 to 180 feet.

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†Figures 2 and 3 will be discussed in more detail in Section I.6.

If it is assumed that the mean value of the elevation has been reduced to zero, then the standard deviation, or root-mean-square (r.m.s.) value of $y(x)$ can in principle be computed by integration of the power spectrum

$$\sigma = \sqrt{\{\text{Ave.}(y^2)\}} = \left[\int_0^\infty \Phi(\Omega)\, d\Omega\right]^{\frac{1}{2}} . \qquad (3)$$

In Reference 1 the power spectra of runway elevation are given for wavelengths ranging from 4 feet to 160 feet ($\pi/80 \leqslant \Omega \leqslant \pi/2$) and, in addition, the values

$$\sigma' = \left[\int_{\pi/80}^{\pi/2} \Phi(\Omega)\, d\Omega\right]^{\frac{1}{2}}$$

are presented. It is suggested in Reference 1 that σ' is a good measure of the average roughness of a runway.

It is easy to show that the magnitude of σ may give a completely wrong impression of the runway quality. This is apparent if a good runway is considered having a slope with respect to a horizontal plane. Such a runway will show a power spectrum with a pronounced peak near $\Omega = 0$ and can have a large value of σ. This peak is cut off in the calculation of σ'. However, Figure 2 indicates, and this was confirmed by a re-calculation for one of the runways of Reference 1, that the magnitude of σ' is nearly completely determined by the part of the integral for values of Ω near the lower boundary (wavelengths near the upper boundary). This means that σ' has little to do with the shorter-wavelength components and cannot be considered as a measure of the average roughness. Since it will strongly depend on the chosen lower limit of Ω, it will even be of dubious value as a basis of comparison for the long-wavelength roughness*.

The power spectral theory has the important feature that it is possible to compute from a given input spectrum (e.g. gust or runway waviness spectrum) the output spectrum of the aircraft response (e.g. acceleration or stress) if certain aircraft characteristics are known, and a few simplifying assumptions are approximately satisfied†. For this reason the power spectrum was considered in Reference 1 to be the most important property of a runway. It is generally considered to yield a good overall picture of the quality of the runway. It is, however, impossible to deduce from the power spectrum the local properties of a runway, e.g. the existence and location of parts in need of repair.

Recently, even the reliability of the power spectrum as an indication of the overall quality of a runway seems to be in doubt. In Reference 2 the responses of a simulated aircraft on two runways having nearly the same power spectra were determined by means

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* σ and σ' will only give a good overall impression on the runway quality if they are computed for a power spectrum that is approximately a white spectrum. This may be the case for the power spectrum of the runway slopes.

† For readers not familiar with the subject the concise and clear summary of power spectral techniques given in Reference 4 is recommended.

of an analogue computer. It appeared that the two runways caused appreciably different aircraft responses; the response was defined as the magnitudes and number of acceleration peaks exceeding 0.5g in absolute value. It is therefore recommended in Reference 2 that the quality of a runway and the location of places in need of repair be determined by means of such analogue computer studies.

The method recommended in Reference 2 has not yet been considered in the work carried out under the auspices of AGARD. Another method of presentation of the measuring results, proposed by the Canadian Panel Member A.H. Hall, has however been used. This method has certain advantages over the power spectrum but it cannot be used for load predictions. The ends of straight lines of various lengths l are put on the runway surface, beginning at one end of the runway, and the lines are then shifted one measuring interval each time until the other end of the runway is reached. For each position of the straight line the vertical distance d between the middle of the line and the corresponding point of the runway surface is determined (Fig.3)*. For each length l the frequency distribution of the absolute values of the deviations d falling within consecutive intervals of 0.01 foot (i.e. 0 to 0.01, 0.01 to 0.02 foot, etc.) are then computed. Figure 3 gives an example of the results so obtained. The percentages for each interval of 0.01 foot are given in the middle of the interval (at l = 48 ft 20 per cent of the deviations d are between 0.02 foot and 0.03 foot). The method of presentation of Figure 3 gives more information on local properties (e.g. maximum deviations exceeding tolerable limits) than the power spectrum, although the location of bad parts of the surface does not appear from the final results.

I.3 RUNWAY ROUGHNESS CRITERIA

The problem of the establishment of criteria which should be satisfied by newly constructed runways or which can be used to determine if a runway is in need of repair has been treated in various papers (Refs.3, 4 and 5). An attempt has been made to base the criteria on a correlation of the results obtained by measuring the runway with the operational experience from the use of the runway. Proposals for criteria in the form of power spectra ($\Phi(\Omega)$ = constant $\times\ \Omega^{-2}$), maximum departures from straight edges of various lengths, and maximum and r.m.s. values of the deviations d defined in Figure 3 have been made.

Serious difficulties arose, however, when the proposed AGARD criteria were submitted for consideration to the NATO Airfields Section, because they were of an entirely different form from the criteria commonly used by runway builders. The NATO criteria for runway construction specify a maximum deviation from the theoretical design profile (which consists of straight lines and transition curves with a specified minimum radius) and maximum departures from a 10 foot straight-edge placed on the runway surface. The main objection against the AGARD proposals was that they were impracticable for checking a runway during construction, in particular as long as time-consuming measurements had to be made. Upon request of the Executive of the Structures and Materials Panel the authors made an attempt to correlate the two sets of criteria. They reached the preliminary conclusion that by a few changes in the numerical values contained in the NATO criteria it would become highly probable that a runway built to these criteria would also conform to the AGARD proposals. No further action has as yet been taken,

* Hence, if the runway length is L_0 and the measuring interval a then the total number of values of d for a straight line of length l is equal to $(1/a)(L_0-l)+1$.

also because the Structures and Materials Panel wished to reconsider the proposed criteria in the light of some new evidence.

I.4 EXISTING RUNWAY AND ROAD MEASURING SYSTEMS

The measurement of runways by means of the classical level-and-rod method takes a long time, viz. about two days per 3300 feet (1 km) with experienced personnel. This fact and the expectation that in future a periodic check of NATO runways in Europe would be necessary, gave rise to the desire of having available a means for obtaining the required data more quickly. At the end of 1959 the principal design requirements for such a measuring system were considered to be:

I.4.1 Measuring speed of the order of walking speed or more.

I.4.2 A range of wavelengths from 4 feet (1.2 m) to 200 feet (60 m) should be covered.

I.4.3 The system should be relatively simple, inexpensive and foolproof in operation.

I.4.4 Preferably, the system should be easily transportable by air.

I.4.5 It should be simple to evaluate the measuring data by means of a digital computer.

I.4.6 The primary final data produced should be the power spectrum of runway elevations. Later on, it was also required to obtain frequency distributions of deviations from straight lines of various lengths. The accuracy of these results should be of the same order as that of the data obtained from the classical method.

I.4.7 The surface profile of a runway need not be obtained to a great degree of accuracy but it should be reproduced 'without loss of wavelengths' in the range mentioned under I.4.2.

Although a review of measuring systems given in Reference 6 had already shown that a system satisfying most of these requirements was unlikely to exist, it was considered useful to review the existing measuring systems again, in particular the European apparatus used for runways and roads, before making a design for a new system.

The conclusions of the study carried out at the NLR were that several European systems enabled a satisfactory measurement of wavelengths up to about 33 feet (10 m) but that no system existed for measuring longer wavelengths. Two of the said systems were the French 'Viagraphe' and the very similar British 'Profilometer'. The latter is shown in Figure 4. It consists of four 4-wheeled carriages and a central box with recording apparatus which remains at a constant height above the average level of the 16 wheels. A measuring wheel can slide freely up and down in the central box and the relative displacement of box and measuring wheel is recorded on a rotating drum. The total length of the Profilometer is 22 ft 6 in (7 m). From a communication by the Road Research Laboratory it was learnt that up to wavelengths of 25 feet (7.5 m) the ratio between the recorded amplitude and the actual amplitude for sine waves is approximately

equal to unity; for longer wavelengths, however, this ratio decreases and is about 0.5 at $L = 40$ ft (12 m). The measuring speed of the Profilometer is about 1 ft/sec (1 km/h).

The French 'Viagraphe' and a 'Mauzin' measuring coach built by the French railways are very similar in principle to the Profilometer. The 'Viagraphe' has one row of 8 equally spaced wheels (spacing 1.43 m = 4.7 ft) and a central measuring wheel. For this system the ratio of measured amplitude to actual wave amplitude when running over a sinusoidal surface of wavelength L is given in Figure 5. It will be seen that reasonable results are obtained for wavelengths in the range from about 5.25 feet to 45 feet (1.6 m to 14 m), but that large errors occur at both shorter and longer waves.

Other measuring systems are based on the recording of the relative displacement of a mass supported by a weak spring in a running cart or of the acceleration of a wheel following the runway surface, but these systems were not considered sufficiently promising to warrant further study.

Interesting information was also obtained on a few systems under development in the United States. A paper design of a simple cart measuring a quantity related to the slope of the runway surface had been made by the N.A.S.A. (see Ref.4). The same principle had meanwhile been adopted at the NLR (see Section I.5). The NASA design was not developed further and the dimensions of the proposed cart were too limited to make it satisfactory for fulfilling the requirements I.4.2 and I.4.6 mentioned before, but this information strongly encouraged the further evaluation of the NLR system.

Already in 1957 the Wright Air Development Center, now Aeronautical Systems Division (A.S.D.), Wright Field, had started the development of a system measuring the elevation of the runway surface with the aid of a horizontal light beam (Refs.6 and 7). The principle is indicated in Figure 6. The system consists of two carts, a stationary one producing the light beam and a running cart carrying the recording apparatus. The 'light cannon' produces a collimated light beam of 3-inch height and 4-inch width (truncated circle) by means of a zirconium element (point source) and a special 'unique' lens. At a distance of 1500 feet these dimensions have grown to 3.75 inch × 10.5 inches. Under favourable circumstances the beam can be used up to a distance of 2000 feet; the normal distance is 1000 feet (300 m). The running cart (speed up to 5 miles per hour) carries a battery of 2 × 5 photocells which automatically centres itself vertically on the light beam, and a profile follower wheel running on the ground surface. The mutual distance between the battery and the wheel is recorded in digital form on a magnetic tape to an accuracy of 0.03 inch (0.75 mm); the smallest measuring interval is 6 inches (15 cm).

The ASD profilometer was not ready for practical application until 1961 and a few interesting results are included in Reference 7. From a comparison with standard level-and-rod measurements over a distance of 300 feet (90 m) it appeared that 84 per cent of the profilometer measurements were within ± 0.2 inch (5 mm) of the level-and-rod data. A comparison of 10 profilometer runs over a distance of 600 feet showed that 67 per cent of the measured elevations reproduced within ± 0.1 inch (2.5 mm).

For the purposes of AGARD the ASD profilometer (apart from the question whether the design would be successfully completed) was considered to be too complicated, too vulnerable and much too expensive.

I.5 CHOICE OF THE PRINCIPLE OF THE NLR MEASURING SYSTEM

When in the beginning of 1960 the results of the study of existing systems were available it was considered which measuring principle was the most promising for fulfilling the requirements mentioned in Section I.4. It had been suggested that the best choice might be the use of an instrumented aircraft, which would have a big advantage owing to its easy transportability. This matter was therefore considered first, and discussed with various bodies where taxiing tests of instrumented aircraft had been carried out or were being planned. It then appeared that such tests were considered to be useful for special purposes, in particular for obtaining data on the transfer function of the tested aircraft or on loads on the aircraft or a similar one. For general purposes, and especially for the measurement of runway roughness properties, an instrumented aircraft was unanimously considered unsuitable. The main disadvantages were formed by the following features:

I.5.1 The evaluation of the measured accelerations or strains is very difficult and uncertain owing to the non-linear properties of an ordinary landing gear. Even when a simple cantilever spring-type undercarriage was used the aircraft properties appeared to depend in an unpredictable way upon the taxi-speed and the nature of the runway.

I.5.2 The aircraft responds mainly to disturbances having a frequency equal to one of its resonance frequencies and tends to filter out all other frequencies. Hence for measuring a wide range of wavelengths a runway should be measured at a number of taxi speeds and possibly a few different aircraft would have to be used.

Finally, the advantage of easy transportability was thought to be illusory and the costs of using an instrumented aircraft high.

Disadvantage I.5.2 also applies to other systems based on measuring accelerations of a spring-mass combination. A relatively simple method of direct measurement of runway elevations over the large range of wavelengths from about 4 feet to 200 feet was not thought to be possible.

The requirements I.4.6 and I.4.7 led to the investigation of the suitability of a slope-measuring system, since the first step in the calculation of the power spectrum is the determination of the differences of successive elevations (pre-whitening), which are used further. This means that in essence the power spectrum of the runway slopes is computed and converted into the power spectrum of the elevations as a final step (post-darkening). It was concluded that all requirements could be satisfactorily met by the use of the slope-measuring principle.

Figure 7 presents a graph of the transfer factor A of a cart having a wheel base a, running over a sinusoidal profile. The transfer factor is defined as the ratio between the amplitude of the slope of the cart and the amplitude of the profile slope. The Figure shows that a/L is an important parameter that should not exceed 0.3 to 0.4 in order to keep the measuring errors within acceptable limits. For measuring the slope of the cart a horizontal reference is required and a satisfactory solution is obtained in the form of a distant light source photographed by a camera mounted on the cart. However, the use of a stationary light source at a great distance has several

disadvantages, so that the properties of the measuring system of Figure 8 were investigated. This system consists of two carts at a constant distance n.a, the one carrying the light source being towed by the measuring cart carrying the camera. Various combinations of n and a were investigated and for the required range of wavelengths ($4 \text{ ft} < L < 200 \text{ ft}$) the values $n = 100$ and $a = 1.5$ ft were selected as the most appropriate combination. The transfer factor of this system is given in Figure 9; for $a/L > 0.3$ the curve coincides with that given in Figure 7.

The suitability of this design was further investigated by carrying out a number of calculations concerning a paper measurement of a known runway by means of a system having $n = 50$ and $a = 2$ ft (which is less accurate). It is to be noted that the deviations d according to Figure 3 and the surface profile must be obtained by integration of the measuring results, so that in principle a cumulation of errors occurs. The results of the calculations showed, however, that both the power spectrum and the frequency distributions of the deviations from straight lines of various lengths were in good agreement with those obtained from the data of level-and-rod measurements. It was therefore decided to build a provisional measuring system and to carry out a number of comparative measurements with the NLR system and precision level-and-rod apparatus.

The accuracy of the slope measurement aimed at was 0.01°, which was considered to be satisfactory on the basis of the calculations carried out. By taking a number of samples of known runway measurements it was concluded that a measuring range of $\pm 3^{\circ}$ would be quite sufficient.

I.6 PROVISIONAL NLR MEASURING SYSTEM AND MEASURING RESULTS

The very simple provisional measuring system, which was intended to evaluate the actual characteristics of the proposed system, is shown in Figures 10 to 13 inclusive. As was already shown in Figure 8, the light source (a flash light with a cross) is photographed by a camera mounted on the small measuring cart proper. The boundary of the image window on the film is used as a reference line, the distance between this reference line and the image of the light source (a small cross) being a measure of the angle between the optical axis of the camera and the light ray. In order to obtain a light flash every 1.5 feet the circumference of the wheels of the camera cart has been made equal to 1.5 feet. A micro-switch (Fig.13, foreground) is actuated once per revolution and gives an electric signal, transmitted along the towing cable to the flash light. At the same time a counter is actuated counting the number of revolutions (Fig.13, right).

The camera used was a continuous camera with variable film speed built at the NLR for other purposes. The lens is always open, which is not objectionable if the measurements are made in the dark or with a clouded sky. However, in order to enable the measurements to be made under sunny weather conditions a butterfly shutter was added driven in a simple mechanical way. Just before the light flashes the shutter is removed laterally and leaves the lens free during a short time (Fig.13).

In Figure 11 the camera cart is shown dismounted from its supporting cart. It is mounted by means of a long pin, and two adjustable spring dynamometers are used to press the camera cart to the ground with a predetermined force (see Fig.12). The wheels of the camera cart are provided with hard rubber tires (70° shore).

A series of runs with the NLR measuring system were made on a part of a runway of 3300 feet (1 km) length at the Air Force Base De Peel. The same stretch was measured with precision level-and-rod apparatus of the 'Rijkswaterstaat'. The cart of Figures 11 and 12 was towed at a constant speed ranging from 1.6 to 6 ft/sec (1.8 to 6.6 km/h) and the force exerted by the spring dynamometers on the camera cart was 22 lb (10 kg) or 66 lb (30 kg). The cart of Figure 10 was towed by the other one by means of a cable also containing the electrical leads, and corrective steering action was taken if necessary. The measurements were made within ± 6 inches (15 cm) approximately from the centre line of the runway and the shots were taken near markings at 1.5 foot spacing on this line, which were also used for making the level-and-rod measurements. The records on the films (consisting of about 2200 crosses and the reference line) were converted into a punched tape by means of a Benson-Lehner Oscar digitizer and the further calculations were carried out on the X-1 digital computer of the NLR. The level-and-rod data were also evaluated on the X-1 after having been punched on a digital tape.

The results of the measurements are presented in Figures 2 and 3. Power spectra were computed for five runs and they showed no systematic effect of the measuring speed or the magnitude of the dynamometer force. All five power spectra showed exactly the same trends, such as the S-shaped parts at $\Omega = 0.3$ and $\Omega = 0.8$. Hence, only the scatterband of the five runs and the power spectrum of run 2 are presented in Figure 2 in comparison with the power spectrum obtained from the level-and-rod data. Run 2 was selected more or less arbitrarily for computing the frequency distributions of Figure 3; it was, however, avoided selecting a run which might present a too optimistic comparison with the level-and-rod data.

The scatter between the five runs in Figure 2 is considered to be small for power spectra, especially if it is observed that the various runs were only approximate repetitions of each other. Up to $\Omega = 0.59$ the maximum scatter factor (maximum $\Phi(\Omega)$ over minimum $\Phi(\Omega)$) is 1.30 and for larger Ω, i.e. smaller wavelengths, the maximum scatter factor is 1.91 at $\Omega = 1.92$. The 'level-and-rod' power spectrum falls outside the envelope of the 5 runs only at a few places. The large discrepancy near $\Omega = 0.035$ is not quite clear, but it is known that at the upper limit of the range of wavelengths ($\Omega = 0.035$) inaccuracies due to the method of calculation may occur, which cannot be considered to be real errors of the measuring system. The most serious discrepancies occur at $\Omega = 0.38$ and $\Omega = 1.12$ where the 'level-and-rod' results are 14 per cent and 15 per cent less than the lower boundary of the 5 runs respectively.

In view of the foregoing it may be concluded that the results of the comparison are quite satisfactory. The same conclusion can be drawn from Figure 3 for the comparison of the frequency distributions.

I.7 CURRENT AND POSSIBLE FUTURE EXTENSIONS OF THE WORK

The work carried out at the NLR for AGARD has been rounded off by the preparation of principal and detail design drawings of a definite version of the measuring system, accompanied by a report containing the manual of the system, a list of requirements for the camera, and data on a commercially available camera. The definite version of the system has been designed such that one or two small tractors can be used to tow the measuring system.

It has been experienced that the most cumbersome part of the evaluation of the measuring data is the conversion of the film into a digital tape. If many sets of measurements would have to be evaluated in the future then it might be worth while modifying the recording apparatus in such a way that the end product of the measuring system is a punched tape instead of a film. Some preliminary thought was given to this problem.

Another problem that was considered provisionally is an extension of the range of wavelengths to a higher upper limit, say about 300 feet. Recent information indicates that components of more than 200 foot wavelength are gaining importance for large modern aircraft. It will be seen from Figure 9 that the transfer factor of the present set-up is satisfactory up to wavelengths of about 500 feet. However, the inclusion of longer waves will necessitate a reconsideration of the programming for the computation of the power spectra, in respect of the amount of work and the accuracy of the calculation. Another method would be to increase the wheel base a (say to 2 feet) in which case there would be less increase of the computational labour but some loss of information in the region of short waves (see Fig.7). Finally, it could be considered adapting both a and n to the desired properties of the system. It is thought that in each particular case the best compromise should be determined in view of the importance attached to the various aspects of the problem.

In Reference 8 some ingenious measurements of the deflection across a runway at Schiphol airport are described when a dead weight of 100 tons was run along the runway at a speed of 5 km/h. These tests were considered of interest in view of the weak structure of the ground in the western part of the Netherlands. One objection that can be made to these measurements is that they give no information on the runway roughness caused by the deflections. The NLR system would be well suited for towing along the runway, both without and with a similar dead weight or a large aircraft, and could thus give an indication of the importance of runway deflections under the load of the aircraft itself for the problem of runway roughness.

PART II

FINAL PHASE OF THE DEVELOPMENT AND TESTING OF THE NLR MEASURING SYSTEM

II.1 INTRODUCTION

After the completion of a series of preliminary tests with a provisional runway roughness measuring system (reported in Ref.9), the AGARD Structures and Materials Panel recommended performing comparative measurements with both the NLR-designed cart and the usual level-and-rod equipment in order to evaluate the merits and disadvantages of the proposed system.

Following this advice the NLR was granted a contract entitled: 'Measurements of the surface irregularities of a segment of a runway of about 1 km (3300 ft) length by means of the NLR measuring system as well as by means of the conventional 'level-and-rod method' (SHAPE-order: 155-62; AGARD Authority: 47/62; date: 15 February 1962).

Thanks to the collaboration of the Dutch Air Force this programme could be carried out on the Air Force Base 'De Peel' in the Netherlands. A series of runs with the NLR measuring system were made on a part of runway 07-25 (length 3300 ft = 1 km). The same stretch was measured by personnel of the Air Force with precision level-and-rod apparatus. All measurements took place during the summer months of 1962.

The cart measurements could be completed in a few days: 10 runs were made with different speeds ranging from 1.6 to 6.0 ft/sec.

Part I of this report gives a general survey and deals with the principal aspects and results of the NLR measuring system.

The present Part describes the philosophy behind the principles of the measuring system and, further, gives a more detailed presentation and discussion of the results of the comparison of the two test series indicated above.

II.2 DESCRIPTION OF THE NLR MEASURING SYSTEM

In References 6 and 10, and in Part I of this report, a survey is given of the existing runway and road measuring systems. It was concluded that most of the equipment considered was unsuitable for the detection of waves with a wavelength of more than, say, 30 feet. An exception was made by a system, the development of which had been started in 1957 by the Wright Air Development Center (Ohio, U.S.A.), now Aeronautical Systems Division (ASD). Details of the system, which can be described as a profilometer, since it measures the elevation of subsequent points of the runway by means of an optical servo-system, are given in Reference 6.

The next possibility considered was the use of an instrumented aircraft with which, e.g., the normal acceleration encountered during taxiing on the runway to be investigated could be recorded. Notwithstanding the possible advantage of easy transportability, the non-linear characteristics of most undercarriages prevented a practical solution of the measuring problem in this way.

The proposal to measure not the elevation of the runway but its slope at the subsequent stations was first published by Houbolt (see, e.g., Ref.4) and arrived at independently at the NLR. Considering this idea it was concluded that slope measuring had the advantage that it avoids the necessity for 'pre-whitening'.

Usually the power density spectrum of the runway elevations shows a sharp decrease when frequency increases. In order to flatten the spectrum to be calculated the series of elevations are replaced by the differences between two neighbouring stations. The power spectrum thus obtained has then to be transformed back to the original spectrum of elevations. This pre-whitening procedure, which is essentially a differentiating process, is performed automatically when slopes instead of elevations are recorded.

Several usual instruments for measuring the slope of a vehicle (pendulum, accelerometer, etc.) appear to be unsuitable because of their sensitivity to accelerations, and therefore an optical method was adopted.

The principle of the system chosen is extremely simple. A camera mounted on a two-wheeled cart (wheels in the same vertical plane) takes pictures of a light source at regular intervals of the runway. The distance of the camera from the light source is so great that it can be considered to be infinite. The position of the picture on the film is a direct measure of the pitch attitude of the cart and thus of the runway slope at the particular moment that the picture is taken.

The assumption that the light source is at an infinite distance from the cart leads to a simple transfer function of the cart. This function is plotted in Figure 7 and a derivation is given in the Appendix. From the graph it follows that long waves are truly reproduced, but that waves with a length approaching the wheel base of the cart are heavily distorted.

Since it is impossible in practice to realize an infinite distance between cart and light source, an investigation was made into how a finite (and constant) distance between the two would affect the transfer function; this is done also in the Appendix and the results are plotted in Figure 9. It is seen that restrictions now also appear at the other end of the wavelength range. Very long waves are almost completely suppressed.

By choosing suitable dimensions for wheel base and distance of light source to cart ($a = 1.5$ ft and $na = 150$ ft) the range of wavelengths specified by AGARD can be reproduced with a very reasonable accuracy: only at the very ends of the spectrum about 2 db distortion occurs (see Fig.9).

According to the above-mentioned analysis the measuring system was realized as follows. A camera of the continuously running type was mounted on a small twin-wheeled platform attached to a cart carrying the power supply for the camera (Fig.11). Both the circumference of the measuring wheels and the distance between their axes amounted to 1.5 feet.

A second cart carrying a flash light was towed by the first one, the distance between the two being 150 feet. This flash light was actuated by a micro-switch on the first cart, thus producing a light signal every revolution of the measuring wheels. To this end the carts were connected by towing cables which served as electrical

connections as well. In order to prevent the film from over-exposure on sunny days a shutter (butterfly type) was mounted before the lens. This shutter was driven by the measuring wheel in such a way that it only opened during a short period of time containing the flash moment.

This system now meets the following primary design requirements:

1. The measuring speed of the cart equals walking speed or more.

2. A range of wavelengths from 4 feet to 200 feet is covered.

3. The system is relatively simple, inexpensive, and fool-proof in operation.

4. The system is easily transportable.

5. The final data, i.e. the power spectrum of the runway elevations, can be produced fairly easily with a digital computer.

A few runs with a preliminary system were carried out at Schiphol Airport with good success; the results are reported in Reference 9, which also contains the drawings of a proposal for a more definite system.

Although the results so far obtained were encouraging, a more definite check on the operation of the system seemed desirable. Accordingly it was decided by the Structures and Materials Panel that a further evaluation should be done by comparing the results obtained with the cart with those of the conventional level-and-rod method. Such an investigation was carried out at the Air Force Base 'De Peel' in the Netherlands and is reported in the next Section.

II.3 RUNWAY MEASUREMENTS AT 'DE PEEL'

II.3.1 General

Thanks to the collaboration of the Dutch Royal Air Force, it was possible to make available a runway on the Air Force Base both for the execution of test runs with the NLR runway roughness measuring cart and for the determination of the profile of runway 07-25 by means of the conventional level-and-rod method. This second part of the work was accomplished by personnel of the Air Forces; the evaluation of the results was done by the NLR.

II.3.2 Slope Measurements with NLR-System

A total of 10 test runs were made with the two carts, the leading one carrying the film camera firmly attached to the measuring wheels (see Fig.14). The trailing cart on which the stroboscopic flash light had been mounted (see Fig.10), was towed by the first one at a constant distance of 150 feet (about 45 m) equalling 100 times the distance between the axes of the measuring wheels. This train was towed along the runway track by hand or by station-car.

Pictures were made at intervals of 1.5 feet so that some 2200 pictures were produced during each run (track length: 1 km or about 3300 ft).

The parameters varied in the programme were the following:

(a) driving speed;

(b) adjustment of springs controlling the force with which the wheels were pressed against the ground.

The aim of these variations was to investigate their effect on the dynamic behaviour of the cart.

A survey of the runs performed on the 19th and 20th of June 1963 is given in Table I. In order to investigate the reproducibility of the measurements a few runs were repeated with the above-mentioned parameters unchanged.

It should be noted that, although all runs were made along the same line approximately at the centre of the runway, lateral deviations of about $\pm$ 6 inches from this line occurred. The runs can therefore not be expected to give exactly identical results. Moreover a longitudinal shift of the measuring stations during the run could not be avoided.

The films obtained were read with a Benson Lehner 'Oscar' reading machine, which allowed the simultaneous production of a punched tape containing (in digital form) the distance of the images of the flash light to a reference line on the film.

For a given focal length of the camera lens ($f = 200$ mm in the present case) it is simple to calculate the slope of the cart and the difference Δy in elevation of the wheels of the cart; summation of Δy then yields the runway profile at an interval of 1.5 ft.

The data thus obtained allow the calculation of the power spectrum of the runway irregularities (for the method applied see Ref.1) and the deviations from straight edges of different lengths. The results of these calculations together with those of the level-and-rod measurements are given in Section II.4.

II.3.3 Level-and-Rod Measurements

After completion of the cart runs the profile of the same runway track was determined by geodetical means, the fieldwork being carried out by the Dutch Royal Air Force.

To this end the track had been provided with paint markings at intervals of 1.5 feet, which had also been used as target marks for taking the shots with the cart. A rod with a centimetre-scale was placed vertically on the markings and was observed through a level instrument, which stood beside the runway. Swivelling of the instrument permitted the measurement of 100 points from one position, after which the level had to be moved to its next station. Reference marks were used to link the different sets of observations together.

The evaluation of the results was done in the same way as described in Section II.3.2 with the exception that the subsequent values of the elevation y had to be subtracted to perform the necessary pre-whitening operation. The quantity Δy thus obtained is equivalent to that directly measured with the cart.

II.4 RESULTS

II.4.1 Power Spectra

The calculation of the power spectra has been performed according to Refeience 1. The scope of the analysis is given in the following table:

Wave length (ft)	*Frequency (rad/ft)*	*Number of power spectral estimates*
L_{min} = 3 (4)	Ω_{max} = 2.09 (1.57)	60 (40)
L_{max} = 180 (160)	Ω_{min} = 0.0349 (0.0393)	

The numbers in parentheses refer to the data of Reference 1.

Although all 10 test runs with the carts have been analyzed, only a part of the results has been incorporated in this report. Figure 2 represents the power spectrum for five runs (2, 5, 6, 8 and 10) covering the various test conditions (see Table I) together with the power spectrum as derived from the level-and-rod measurements. It can be seen from the Figure that the agreement between the results of the two methods is very good (see e.g. the S-shape in the curves at $\Omega = 0.8$), except for the very long wavelengths. This is also shown by Table II, which gives the numerical power spectral estimates for test run No.2 and the level-and-rod measurements.

The Figure further shows that no systematic effects of driving speed and spring tension on the results occur. Thus it can be concluded that a driving speed of somewhat more than walking speed is quite acceptable and that the magnitude of the spring tension is not critical.

II.4.2 Straight Edge Deviations

A practical method to appreciate the quality of a runway is to put a straight edge at its surface and to measure the gap between runway and edge in the middle of the edge. A usual length of such a rod is 10 feet and a tolerable gap is of the order of 0.1 inch. It is, however, clear that this procedure only gives information on the presence of relatively short waves in the runway surface. For the detection of longer waves impractically long edges would have to be used. For a numerically given runway the gaps under or deviations from imaginary straight edges at their centres can easily be calculated (see Fig.3).

The total number of deviations found for a particular straight edge of length l (ft), when it is shifted one measuring interval each time from the beginning to the end of the runway, amounted to

$$N - \frac{l}{a}$$

where N is the number of measuring stations at intervals of a (ft).

The next step was the determination of the percentages of deviations of different magnitudes (0 to 0.01 ft; 0.01 to 0.02 ft; etc.). The resulting distribution curves were calculated for straight edges of the following lengths: 12, 18, 30, 48, 75, 120 and 180 feet. The results are given in Table III and an illustration is given in Figure 3 both for the cart and for the level-and-rod measurements.

The agreement between the results from cart and level-and-rod measurements is excellent for the shorter edges and quite satisfactory for the longer ones.

II.4.3 Runway Profile

The results of the cart runs permit the derivation of the runway profile by simply adding the measured elevation differences Δy, whereas the level-and-rod measurements directly yield the elevations y. Since a constant slope (infinite wavelength) is not measured by the cart system, both sets of results have been determined with respect to the 'mean slope profile', i.e. the straight line connecting the first and the last point of the profile.

The results are given in Figure 15; the top curve represents the profile as derived from run 2 of the cart measurements and the bottom curve refers to the level-and-rod measurements. Since complete reproduction of all elevations appeared to be impracticable, each fifth point (7.5 ft apart) has been plotted on the Figure. At first sight the agreement between the two curves seems to be poor and this is certainly true for the very-long-wave contents of the profile. In particular the long wave occurring in the level-and-rod profile between the 800 and 1500 foot stations, which appears to have a wavelength of about 1000 feet, does not show up in the upper profile. It must be remembered, however, that according to Figure 9 very long waves are largely suppressed by the cart system and thus cannot be expected to appear in the measured profile. A closer inspection of the curves of Figure 15 shows that for the required range of wavelengths the similarity of the two profiles is remarkably good.

Summarizing, it can be noted that apart from the components, which the cart is inherently unable to record, the characteristics of the runway profile are reproduced in a quite acceptable way.

II.4.4 Accuracy Aspects

The use of a camera with a lens having a focal length of 8 inches (200 mm) makes it possible to obtain an accuracy of some 0.01° in the measured slope angle of the cart. For a wheel base of 1.5 feet this corresponds to a scatter of a fraction of 0.001 foot in the elevation difference as derived from the slope.

This error magnitude is somewhat better than that for the profiles measured on several NATO airports with level-and-rod equipment (see e.g. Ref.11). Although the resolution of the equipment used at the 'Peel' airport was many times higher, it is believed that higher accuracies than mentioned above are not worth aiming at, since the incidental changes of the surface (due to stones, dust, etc.) make these accuracies meaningless.

Apart from the direct errors in the measured data there is another source of inaccuracy, which stems from the finite length of the runway sample considered. The magnitude of this error is dependent on the following two parameters:

(a) length of the sample;

(b) band width of the power spectral estimates;

(a) This influence is easy to understand: the longer the sample the more reliable the power spectral estimate will be.

(b) The use of a narrow filter (small band-width) results in a larger scatter in the power estimates. This can be understood when it is realized that reducing the band-width of the filter used (in this report of the mathematical type) increases the amount of information extracted from the same source of given data. So it is clear that the reliability of each individual power estimate is bound to go down.

In Reference 12 a formula is given for the standard deviation σ_Φ of the power estimates, reading

$$\frac{\sigma_\Phi}{\Phi} = \frac{1}{\sqrt{(BT)}}$$

where B = band-width of filter (cps)
T = sample length (sec).

If this formula is applied to the underlying case (sample length: 3300 ft and band-width: 0.035 rad/ft) then a standard deviation between 20 and 25 per cent is found.

It is interesting to note that even for a runway of 10,000 feet the standard deviation of the power estimates is still some 14 per cent. These figures show that it is impossible to improve the reliability of the final results by merely increasing the accuracy of the measurement of runway elevation or slope.

II.5 CONCLUSIONS AND RECOMMENDATIONS

The conclusion that can be drawn from the reported investigation is that good agreement exists between the results obtained by:

(a) level-and-rod measurements of about 3300 feet of a runway of the Air Force Base 'De Peel';

and

(b) the corresponding measurements with the NLR-cart system on the same runway track.

This is true in particular for the power spectral density of the irregularities and the distribution of straight edge deviations (see Figs. 2 and 3 respectively). The runway profile itself is not truly reproduced by the cart system as far as very long waves in the runway surface are concerned (Fig. 15). This is in accordance with the transfer characteristics of the system as displayed in Figure 9. The object of a true reproduction of waves with a length of the order of 3 to 200 feet, however, has been achieved successfully.

No significant effects of driving speed of the cart or spring load on the measuring wheels appeared from the results of 10 test runs. A driving speed of somewhat more than walking speed seems to be quite practicable. This corresponds to a measuring time of about half an hour for a runway of 10,000 feet. For the same length, level-and-rod measurements take about a week for a team of at least two men.

A weak point in the procedure with the cart is data handling: conversion of the film pictures to a (digital) punched tape suitable for feeding into an electronic computer involves a cumbersome job of film-reading. When many sets of measurements have to be evaluated it is recommended modifying the system in such a way that instead of a film a punched tape should be the product of the system.

Finally, it must be remarked that there is some indication from recent investigations (e.g. by NASA) that the power spectrum of the irregularities in particular is not always a good criterion for the quality of the runway and that other criteria have to be considered. It seems to be worth while investigating the possibilities of the cart system with respect to proposals in this field as soon as they have reached a firm status. Further, still longer waves (up to 300 ft or even more) might appear to be of importance, and reconsidering the design might then be desirable.

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APPENDIX

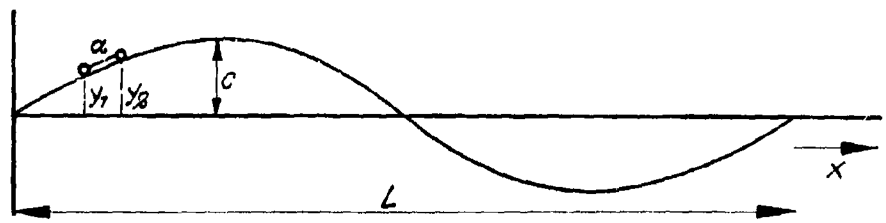
DERIVATION OF THE TRANSFER CHARACTERISTICS OF THE MEASURING CART SYSTEM

When a simple slope measuring vehicle with a wheel base a (see first sketch) moves along a sinusoidally curved path given by

$$y = C \sin 2\pi \frac{x}{L}$$

the slope measured by the cart can be written as

$$\phi_{meas} \approx \frac{y_2 - y_1}{a} = \frac{2C}{a} \sin \frac{\pi a}{L} \cos \frac{2\pi(x + \frac{1}{2}a)}{L} .$$



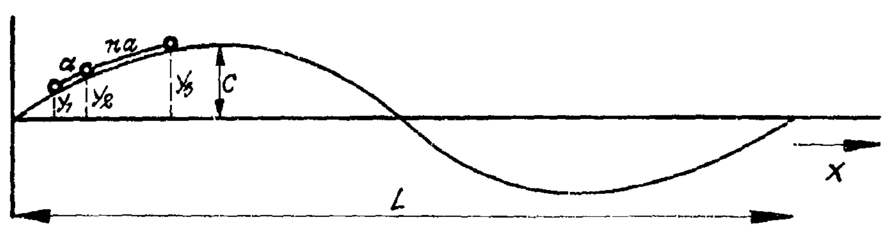
Since the actual slope of the path equals

$$\frac{dy}{dx} = \frac{2\pi C}{L} \cos \frac{2\pi x}{L}$$

the amplitude ratio A of measured and actual slopes can be given by

$$A = \frac{|\phi_{meas}|}{|\phi_{act}|} = \frac{\sin(\pi a/L)}{\pi a/L} . \qquad \text{(A-1)}$$

It can be seen that waves with a length L which is large relative to the wheel base a are truly reproduced (see Fig.7).



If the real horizon is replaced by a point on the surface at a distance n times a from the cart (see second sketch) the transfer characteristics of the system change considerably.

The apparent slope angle now measured can be approximated by

$$\phi_{meas} \approx \frac{y_2 - y_1}{a} - \frac{y_3 - y_2}{na} \, . \qquad \text{(A-2)}$$

Substitution of

$$y_1 = C \sin \frac{2\pi x}{L}$$

$$y_2 = C \sin \frac{2\pi(a + x)}{L}$$

and

$$y_3 = C \sin \frac{2\pi(na + a + x)}{L}$$

in (A-2) shows that ϕ_{meas} varies sinusoidally with x . The amplitude of this sine wave can be reduced to

$$|\phi_{meas}| = \frac{2C}{a}\sqrt{\sin^2\frac{\pi a}{L} + \frac{1}{n^2}\sin^2\frac{\pi n a}{L} - \frac{2}{n}\sin\frac{\pi a}{L}\sin\frac{\pi n a}{L}\cos\frac{\pi(n + 1)a}{L}} \, .$$

The amplitude ratio of measured and actual slope now becomes

$$A = \sqrt{\left(\frac{\sin(\pi a/L)}{\pi a/L}\right)^2 + \left(\frac{\sin(\pi n a/L)}{\pi a n/L}\right)^2 - 2\,\frac{\sin(\pi a/L)}{\pi a/L}\,\frac{\sin(\pi n a/L)}{\pi n a/L}\cos\frac{\pi(n + 1)a}{L}} \, .$$

This function has been plotted in Figure 9 of this report for the case $n = 100$.

TABLE I

Test Runs Executed at the Air Force Base 'De Peel'
(June 19th and 20th 1963)

Run No.	Aver. driving speed		Spring tension	
	m/sec	*ft/sec*	*kg*	*lb*
1	0.5	1.7	10	22
2	0.5	1.7	30	66
3	0.55	1.8	30	66
4	1.2	4.0	30	66
5	1.8	6.0	30	66
6	1.55	5.2	10	22
7	1.8	6.0	30	66
8	1.1	3.7	10	22
9	0.75	2.5	10	22
10	1.8	6.0	30	66

TABLE II

Power Spectral Estimates as Derived from Cart (Run 2) and Level-and-Rod Measurements

Ω (rad/ft)	L (ft)	$10^5\phi(\Omega)$ (ft^2/rad/ft) cart	$10^5\phi(\Omega)$ (ft^2/rad/ft) lev. + rod	Ω (rad/ft)	L (ft)	$10^5\phi(\Omega)$ (ft^2/rad/ft) cart	$10^5\phi(\Omega)$ (ft^2/rad/ft) lev. + rod
0.0349	180	1030	4323	1.08	5.8	0.92	0.90
0.0698	90.0	355	322	1.12	5.6	0.78	0.64
0.105	60.0	155	141	1.15	5.5	0.73	0.50
0.140	45.0	67.4	61.6	1.19	5.3	0.66	0.55
0.175	36.0	36.8	33.0	1.22	5.1	0.60	0.64
0.209	30.0	23.1	21.7	1.26	5.0	0.56	0.63
0.244	25.8	14.2	14.0	1.29	4.86	0.50	0.65
0.279	22.5	9.86	8.97	1.33	4.74	0.48	0.73
0.314	20.0	8.32	7.10	1.36	4.62	0.49	0.60
0.349	18.0	8.29	6.66	1.40	4.50	0.46	0.46
0.384	16.3	6.76	5.56	1.43	4.39	0.40	0.42
0.419	15.0	5.11	4.98	1.47	4.29	0.43	0.43
0.454	13.8	4.60	4.82	1.50	4.19	0.50	0.52
0.489	12.9	3.63	3.82	1.54	4.09	0.51	0.58
0.524	12.0	2.48	2.74	1.57	4.00	0.48	0.59
0.559	11.2	1.74	2.06	1.61	3.91	0.43	0.56
0.593	10.6	1.40	1.70	1.64	3.83	0.37	0.50
0.628	10.0	1.35	1.64	1.68	3.75	0.33	0.45
0.663	9.5	1.20	1.32	1.71	3.68	0.40	0.43
0.698	9.0	1.02	1.06	1.75	3.60	0.50	0.53
0.733	8.6	1.01	1.13	1.78	3.53	0.47	0.62
0.768	8.2	1.03	1.14	1.82	3.46	0.42	0.52
0.803	7.8	1.10	1.11	1.85	3.40	0.43	0.35
0.838	7.5	1.19	1.14	1.88	3.34	0.44	0.32
0.873	7.2	1.29	1.19	1.92	3.28	0.42	0.40
0.908	6.9	1.19	1.10	1.95	3.22	0.46	0.43
0.942	6.7	0.91	0.93	1.99	3.16	0.44	0.42
0.977	6.4	0.77	0.80	2.02	3.10	0.38	0.47
1.01	6.2	0.79	0.74	2.06	3.05	0.34	0.57
1.05	6.0	0.93	0.89	2.09	3.00	0.31	0.62

TABLE III

Distributions of Straight Edge Deviations Derived from Cart and Level-and-Rod Measurements

Straight edge length (ft)	*Deviation between ($10^{-2}ft$)*	*Percentage*	
		cart	*lev. + rod*
12	0 – 1	77.1	77.3
	1 – 2	20.3	20.0
	2 – 3	2.5	2.6
	3 – 4	0.1	0.1
18	0 – 1	64.2	65.4
	1 – 2	27.9	26.6
	2 – 3	6.4	7.1
	3 – 4	1.4	0.9
	4 – 5	0.1	–
30	0 – 1	47.4	48.7
	1 – 2	33.0	32.1
	2 – 3	12.6	13.1
	3 – 4	4.9	4.4
	4 – 5	1.6	1.4
	5 – 6	0.5	0.3
48	0 – 1	33.1	35.0
	1 – 2	28.8	27.3
	2 – 3	18.6	19.5
	3 – 4	10.2	11.0
	4 – 5	5.4	4.5
	5 – 6	2.8	2.0
	higher	1.1	0.6
75	0 – 1	24.4	25.2
	1 – 2	23.0	23.7
	2 – 3	19.6	19.2
	3 – 4	14.1	13.6
	4 – 5	9.0	10.6
	5 – 6	6.6	4.6
	higher	3.3	3.1
120	0 – 1	21.7	23.3
	1 – 2	21.7	20.7
	2 – 3	17.8	17.4
	3 – 4	13.8	14.6
	4 – 5	9.8	10.6
	5 – 6	6.5	5.7
	higher	8.7	7.7
180	0 – 1	15.7	19.6
	1 – 2	16.9	17.6
	2 – 3	17.9	15.5
	3 – 4	13.0	14.5
	4 – 5	10.2	11.8
	5 – 6	10.5	7.2
	higher	15.8	13.8

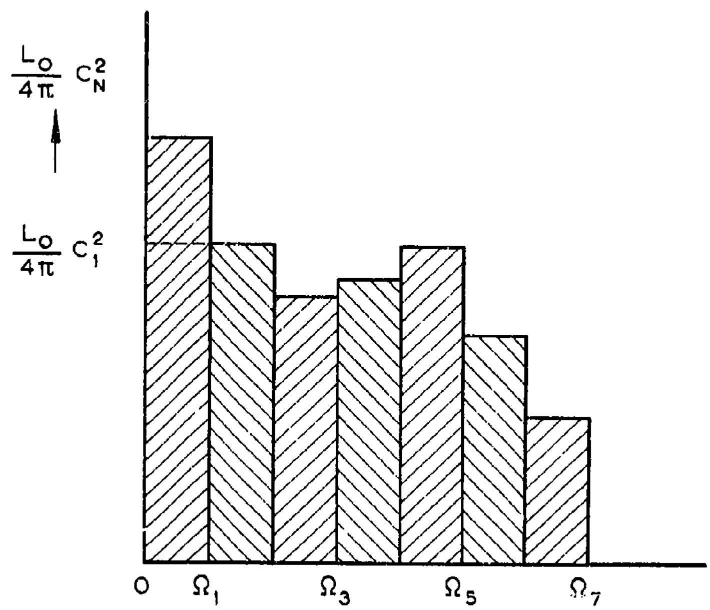


Fig. 1 Discrete energy or power spectrum

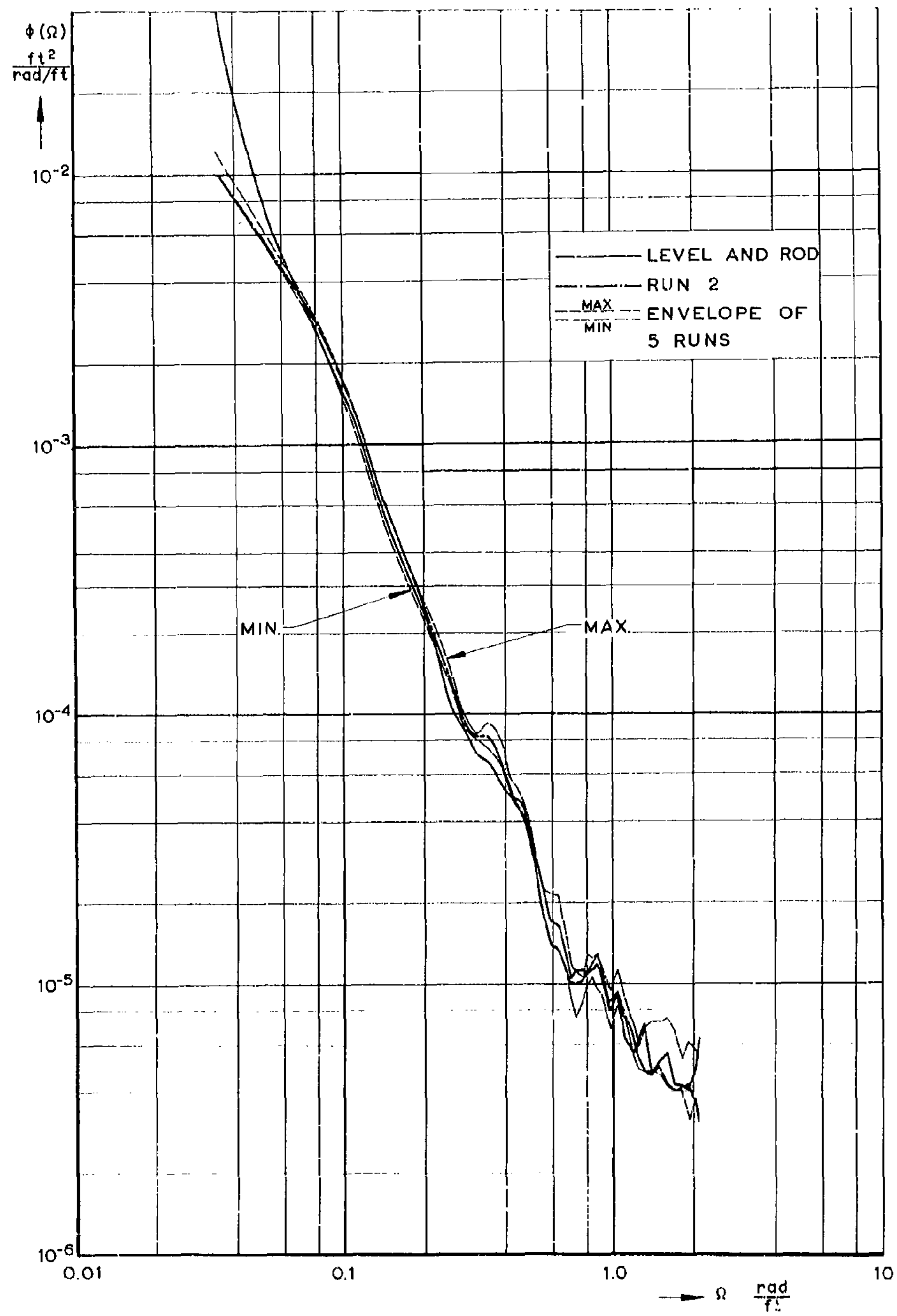


Fig.2 Power spectra of runway elevations

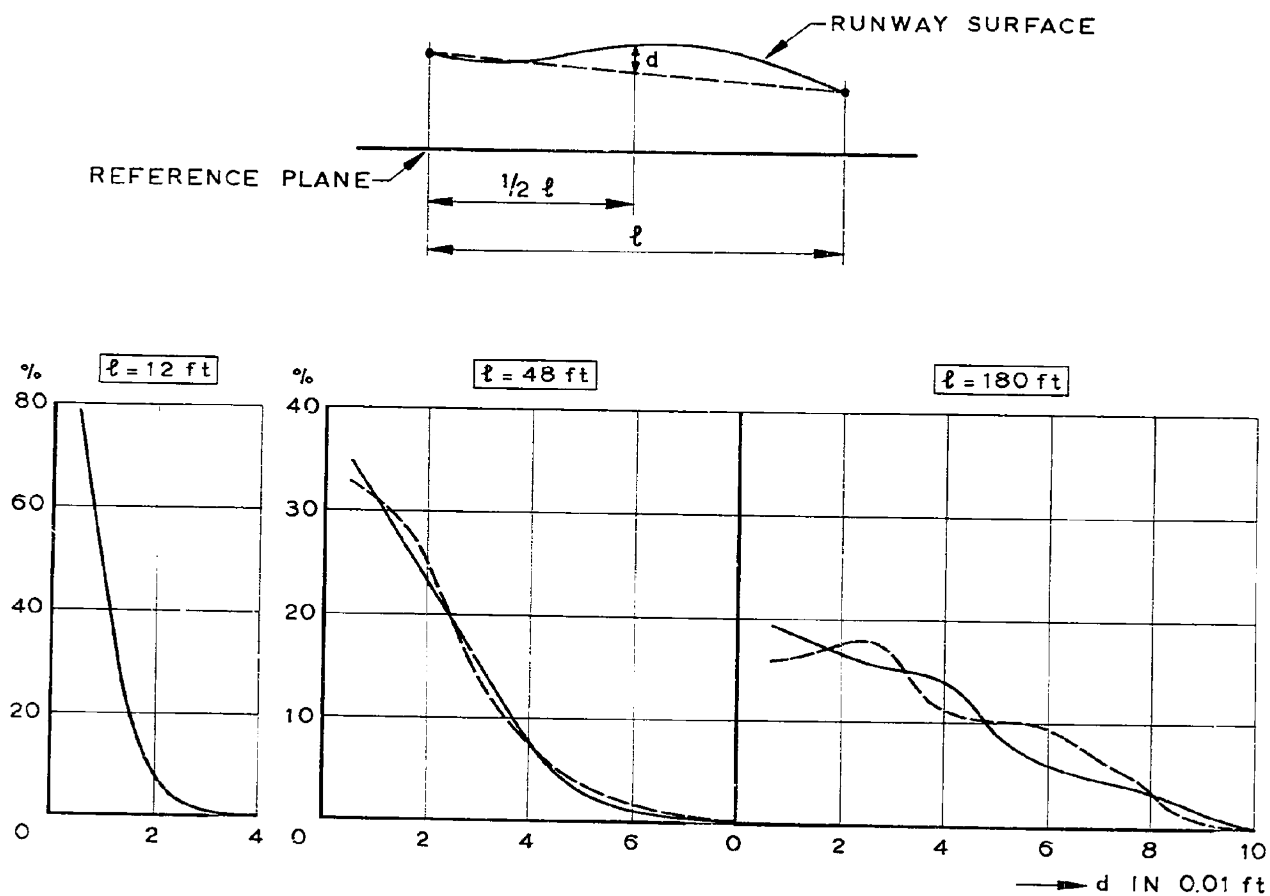


Fig.3 Frequency distributions of absolute values of deviations d from straight lines of various lengths ℓ

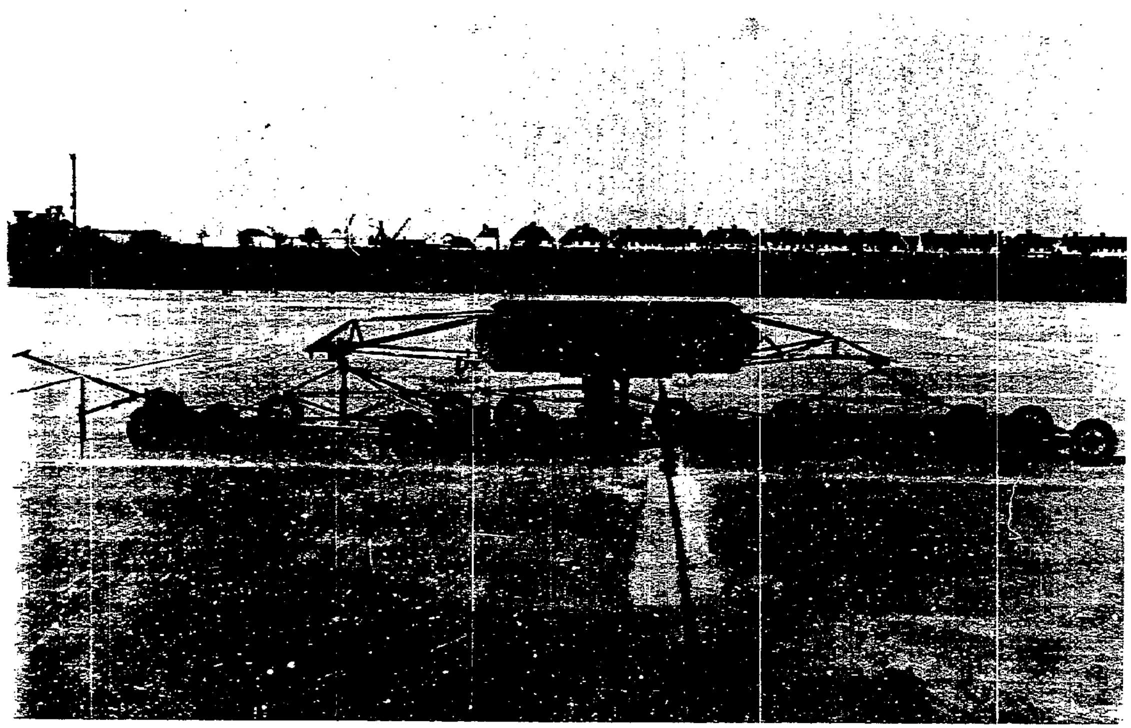


Fig. 4 Profilometer of the Road Research Laboratory

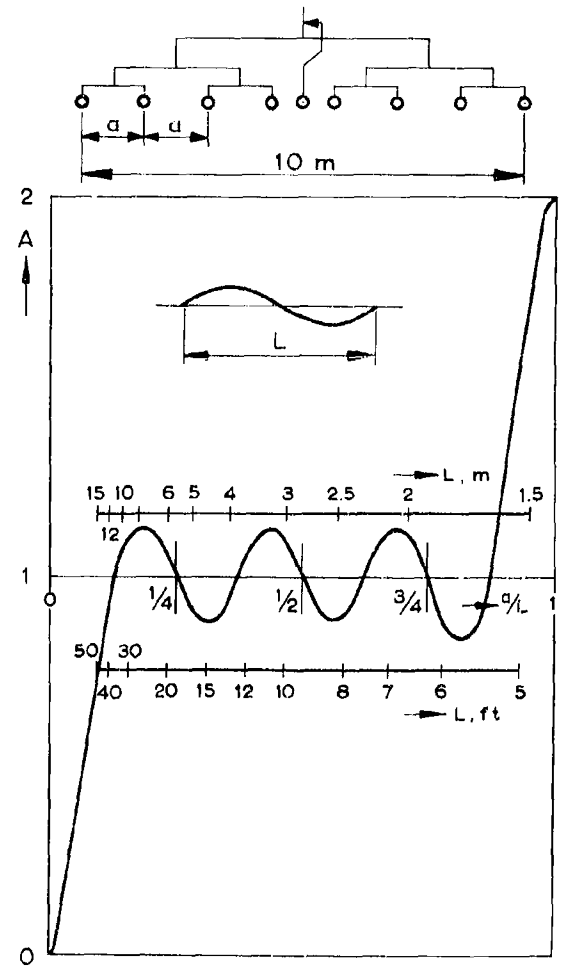


Fig.5 Transfer factor of Viagraphe

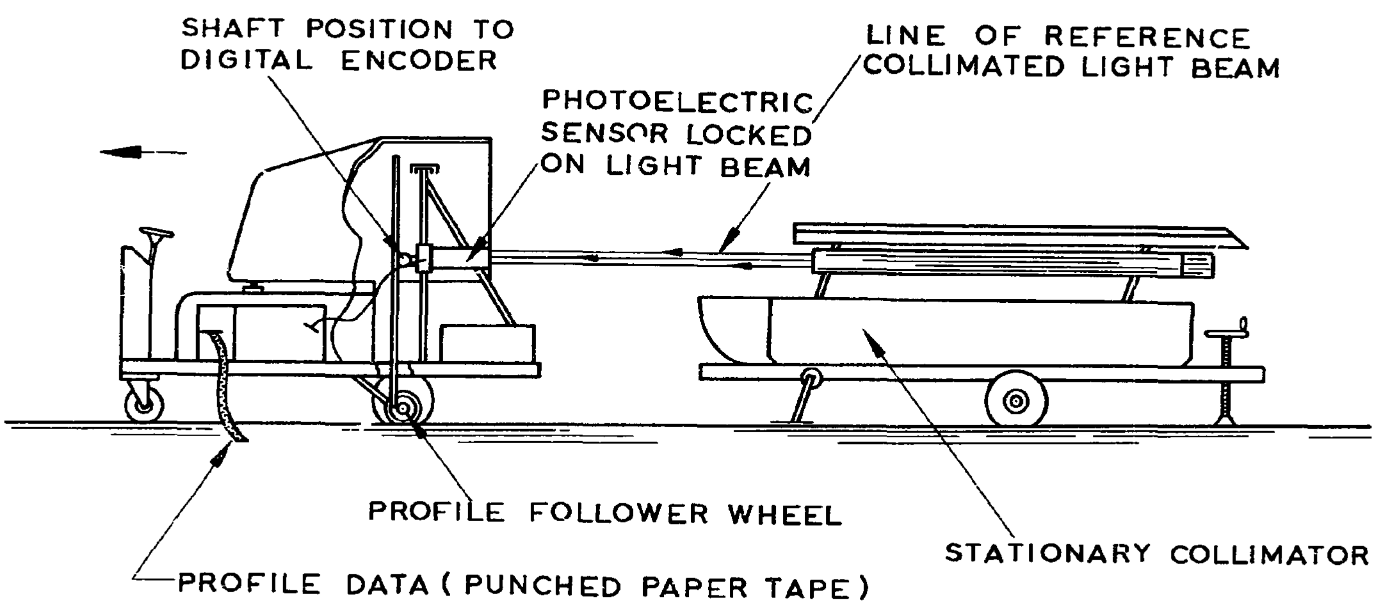


Fig.6 Principle of measuring system of Aeronautical Systems Division,
Wright-Patterson A.F. Base

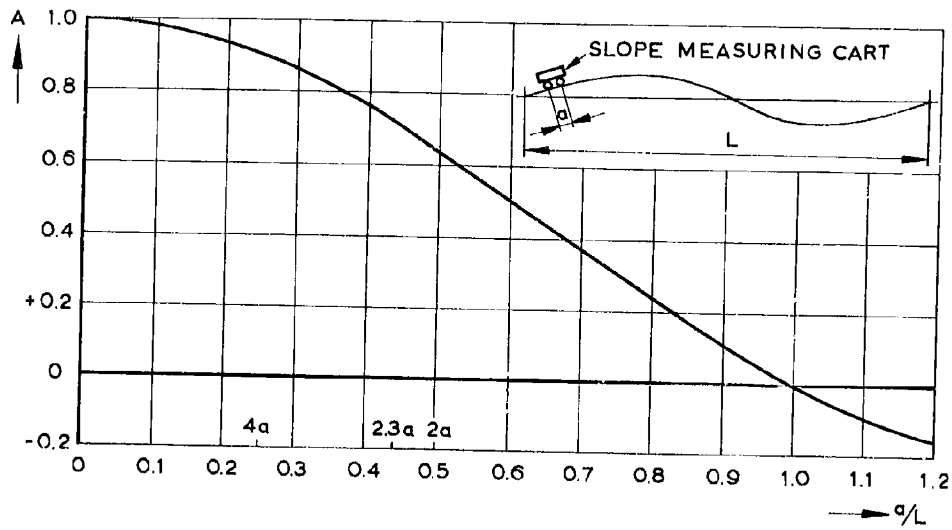


Fig. 7 Transfer factor of simple slope measuring cart

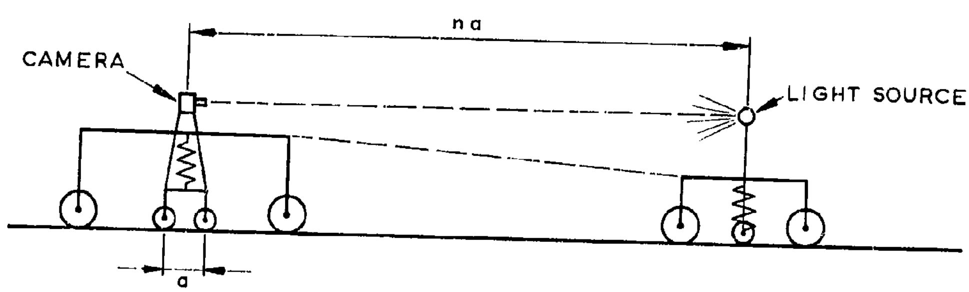


Fig. 8 Principle of NLR slope measuring system

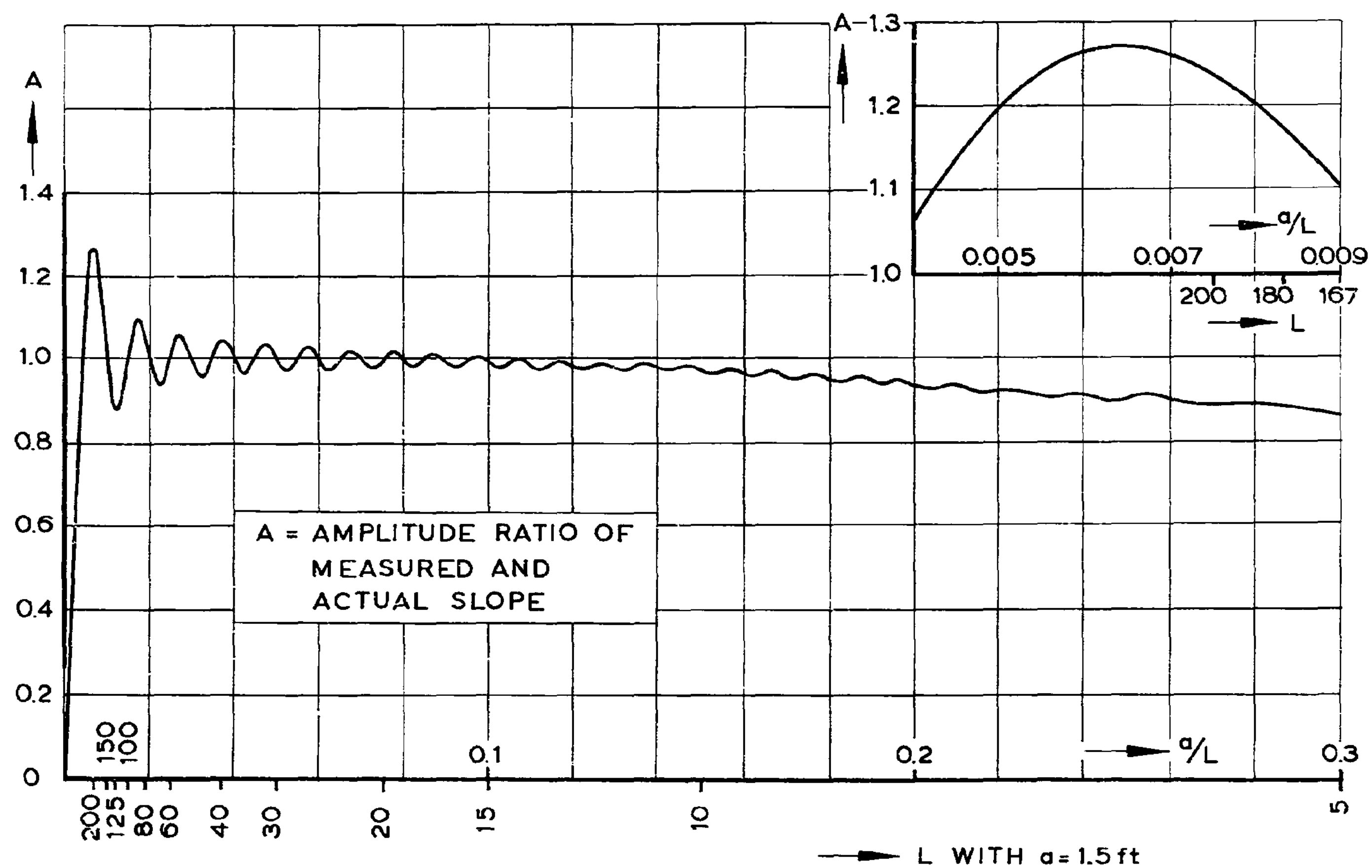


Fig.9 Transfer factor of NLR system with n = 100

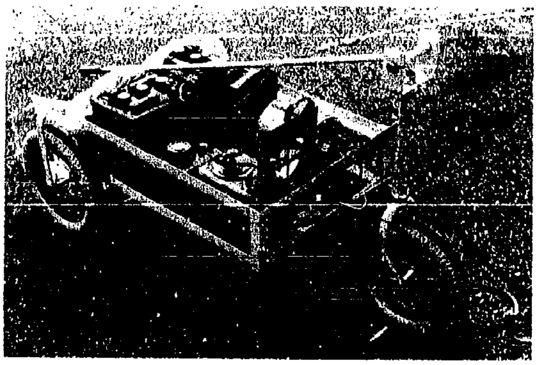


Fig.10 Cart carrying flash light

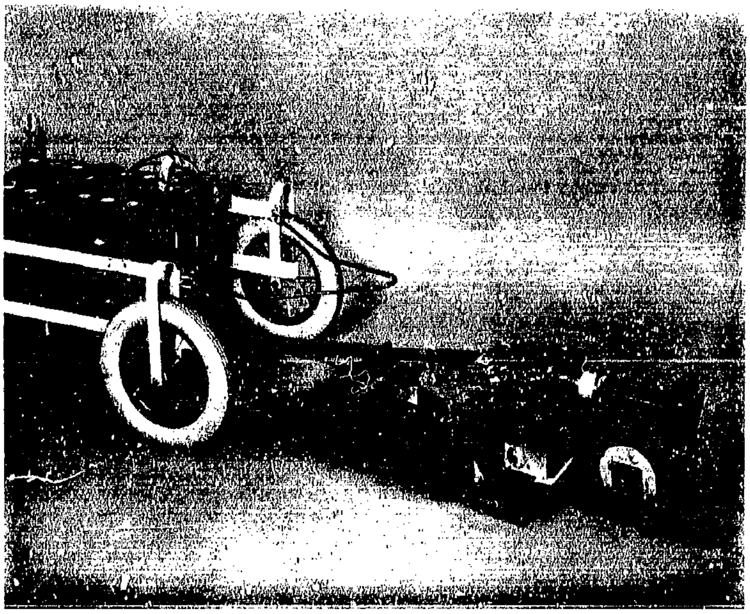


Fig.11 Camera cart dismounted from its supporting cart

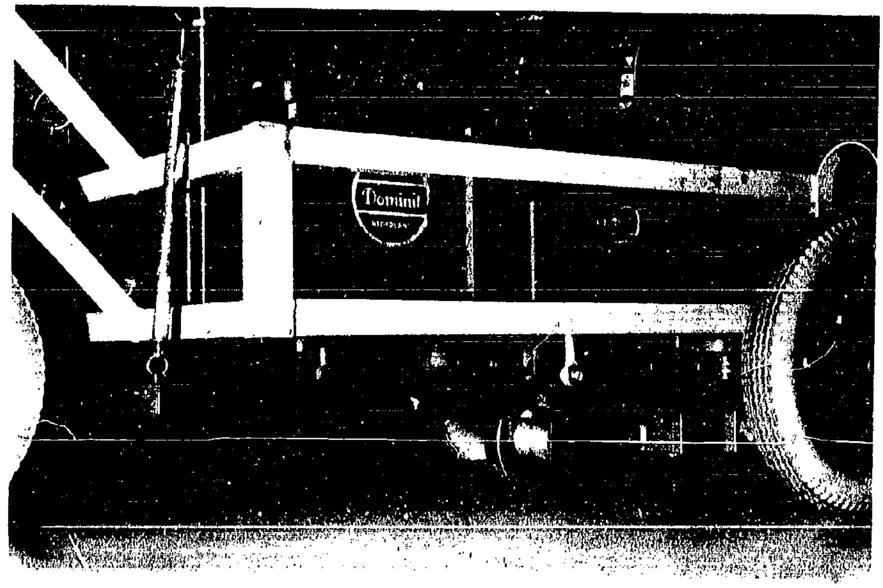


Fig.12 Detail of mounting of camera cart

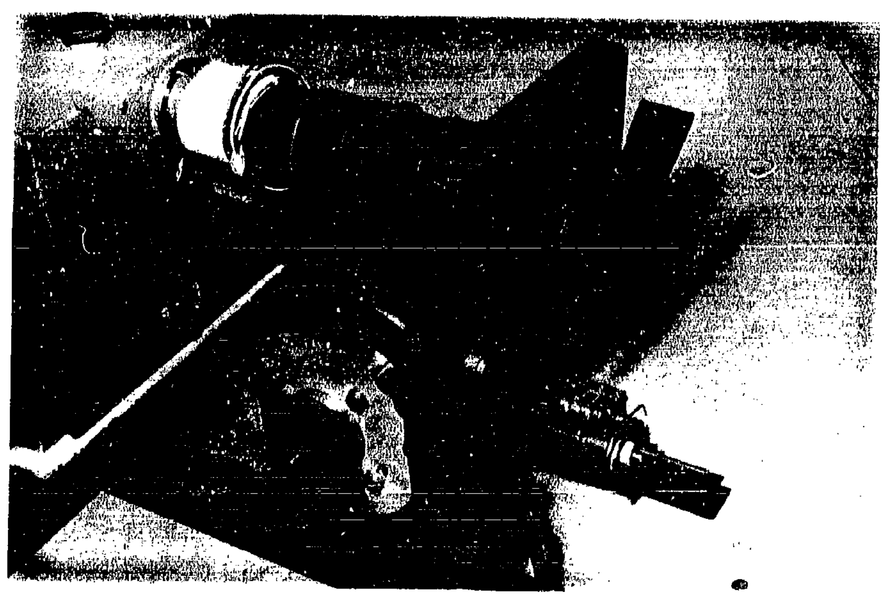


Fig.13 Detail showing camera, butterfly shutter, counter and measuring wheel with micro-switch

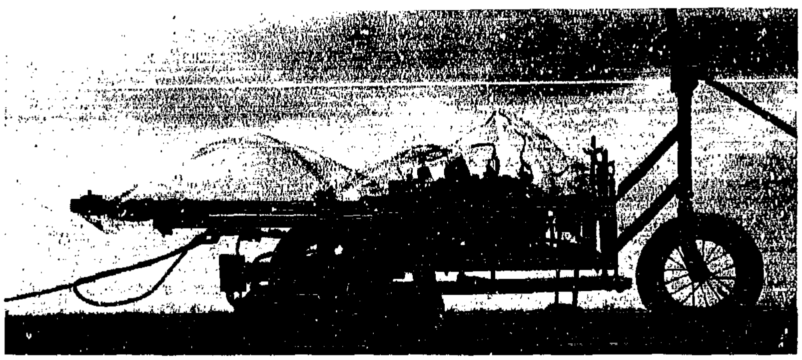


Fig.14 Camera cart ready for operation at 'De Peel'

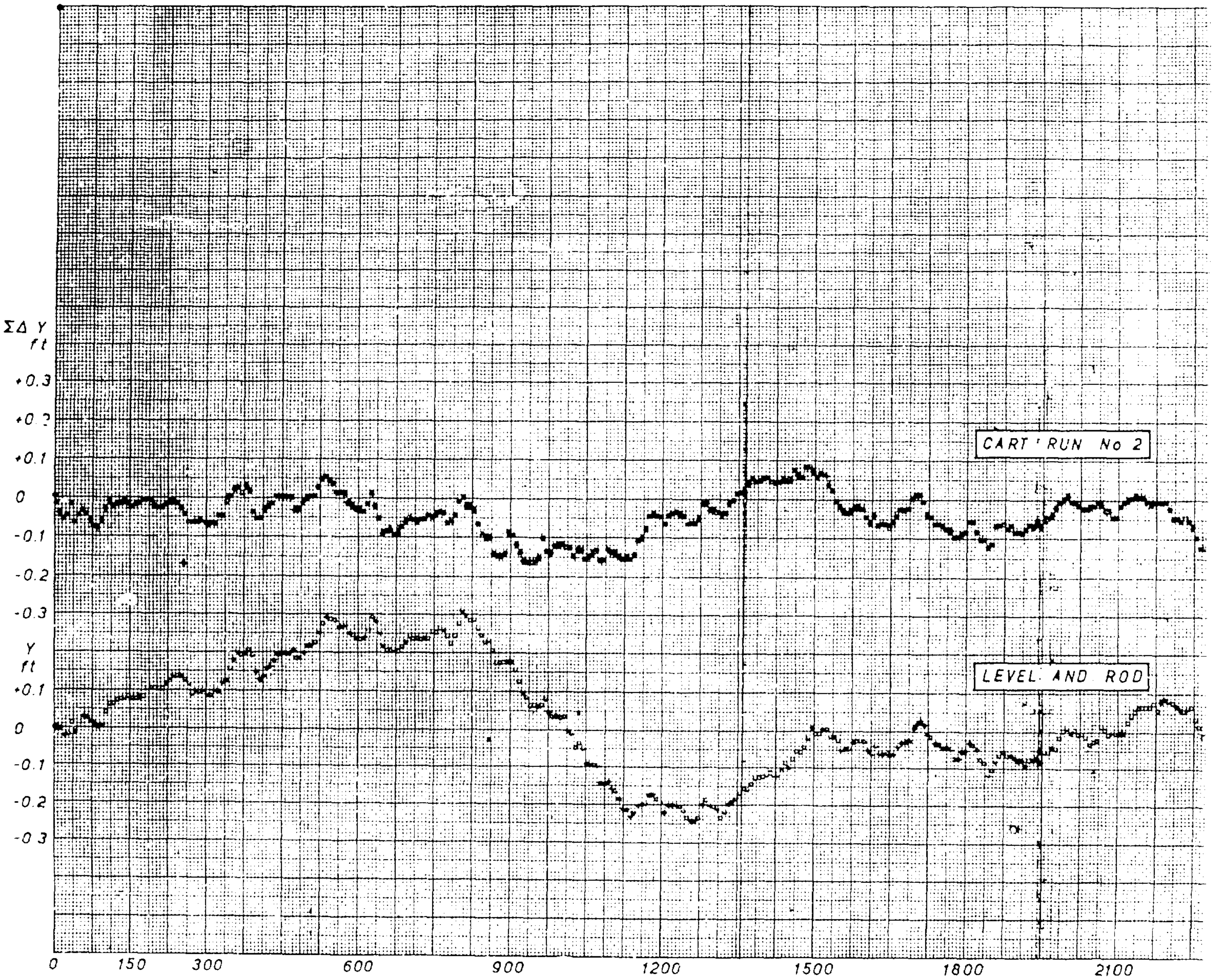


Fig.15 Comparison of runway profil

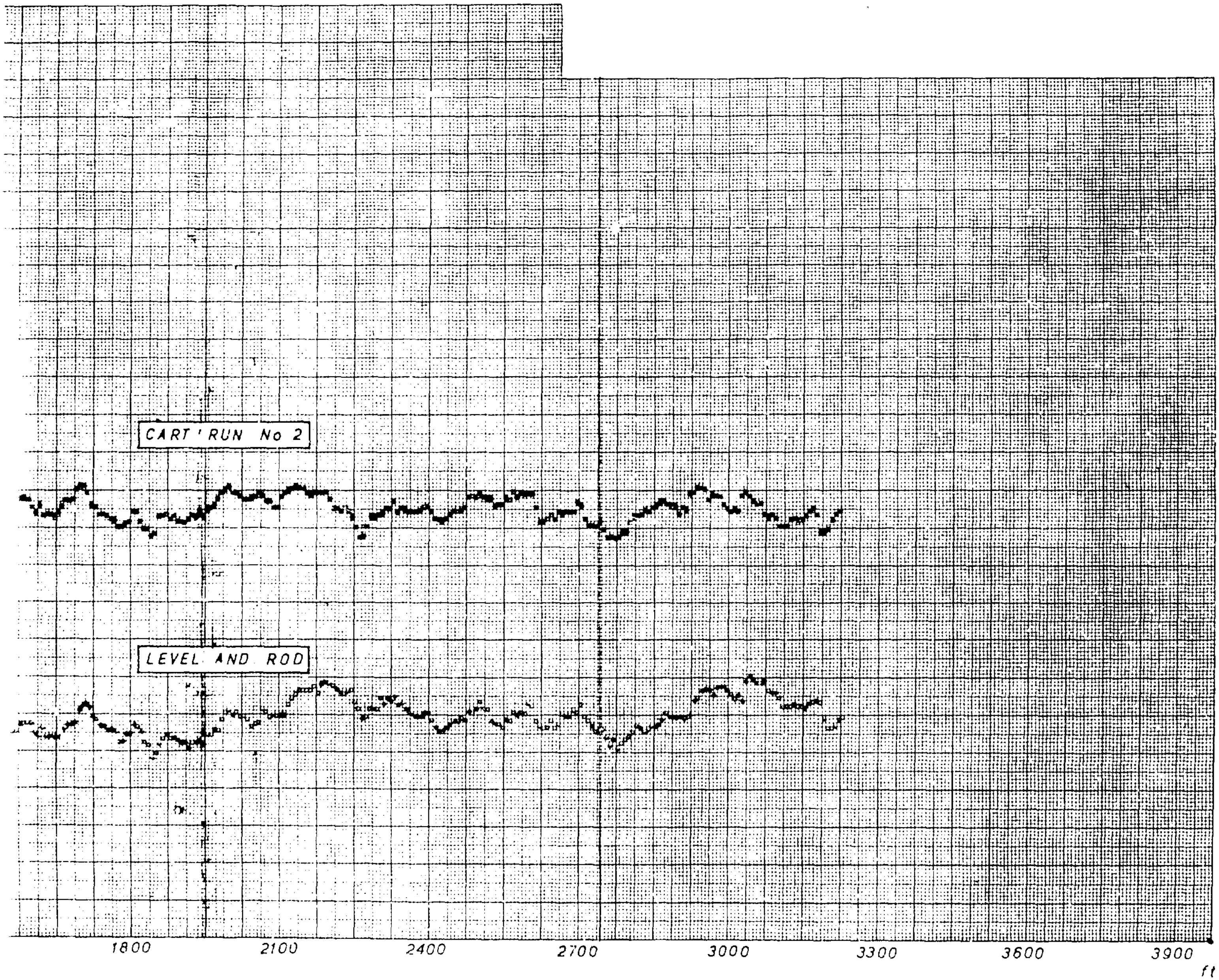


Fig.15 Comparison of runway profiles

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The results of a series of test runs with the NLR-system are compared with the results of conventional level-and-rod measurements. The agreement between the derived characteristics (power spectrum and deviations from straight lines) is very satisfactory. The agreement between the runway profile as obtained by integration of the measured slopes and the true profile is limited, since the system only gives a true reproduction of the components in the design range of wavelengths.

It is concluded that the NLR-system shows favourable characteristics as a rapid and simple measuring system. A few current and possible future extensions of the work are dealt with briefly.

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F.J. Plantema and J. Buhrman
1963
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A review is given of the work concerned with surface waviness of runways and taxi-tracks carried out under the auspices of the Structures and Materials Panel of AGARD. The collection of statistical data and the advantages and disadvantages of various forms of presentation of these data are discussed. Runway roughness criteria are dealt with very briefly.

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